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13. ABSTRACT *(Maximum 200 words)*

This is the final report describing the objectives and accomplishments of the research conducted under the above referenced grant. The general purpose of this grant has been to study a novel approach to active vibration control in helicopter fuselages known as the Active Control of Structural Response (ACSR) approach. In this approach vibrations in the helicopter fuselage are reduced by introducing harmonically varying forces by actuators located between the rotor and the fuselage such that the sum of the response of the airframe, due to rotor loads and external excitation, is reduced to a minimum. The primary objectives of this research were: (1) development of a coupled rotor/flexible fuselage model capable of simulating the vibrations in the fuselage and their control using the ACSR system, (2) modeling of the closed loop vibration reduction using two different control algorithms, a simple algorithm denoted the BACSR-algorithm, and a more refined algorithm based upon the internal model principle, denoted as the IMP-algorithm, and (3) conduct trend studies, to demonstrate vibration reduction throughout the flight envelope of the helicopter. All the objectives stated were achieved in the course of the research. Reduction of vibration levels below 0.04g was demonstrated throughout the flight envelope, with relatively modest control effort, and low control power requirements. This research also provided a fundamental understanding of the approach that was not available from the experimental and empirical studies conducted before.

14. SUBJECT TERMS
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BACKGROUND AND OBJECTIVES

Recently a new approach to active control of vibrations in helicopter fuselages has emerged. This method which is based on the concept of direct control of structural response, is denoted by the term Active Control of Structural Response (ACSR), and it was developed initially by Westland. The ACSR scheme is based on the idea that in a linear system one can superimpose two independent response quantities such that the total response is zero. When applying this scheme to the helicopter vibration reduction problem the fuselage, at selected locations, is excited by controlled forcing inputs, such that the combined response of the fuselage, due to rotor loads and the applied excitation will be minimized.

The schematic representation of such a coupled rotor/active control/fuselage dynamic system is shown in Figs. 1 and 2. Figure 1 depicts the coupled rotor/flexible fuselage system and Fig. 2 shows the control loop used for vibration reduction. In this approach the rotor and gearbox are mounted on the top of the rigid platform shown in Fig. 1, and the vibration suppression is achieved by the four actuators, shown in vertical dark lines in Fig. 1. These actuators are located at

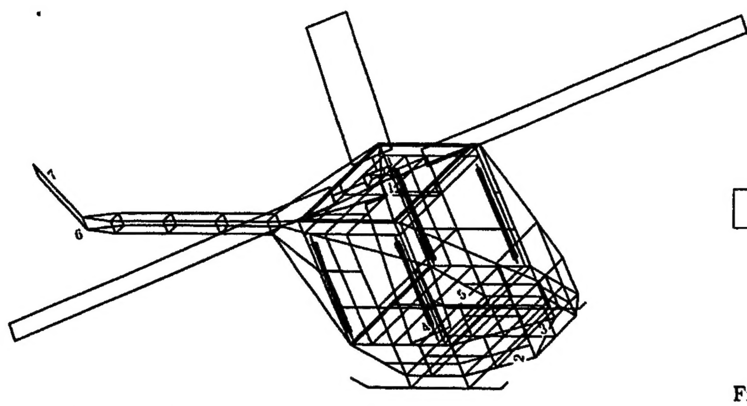

Figure 1: Coupled rotor/active control/fuselage dynamic system

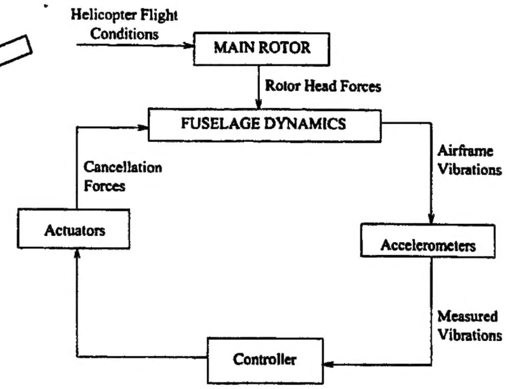

Figure 2: Schematic representation of the ACSR system

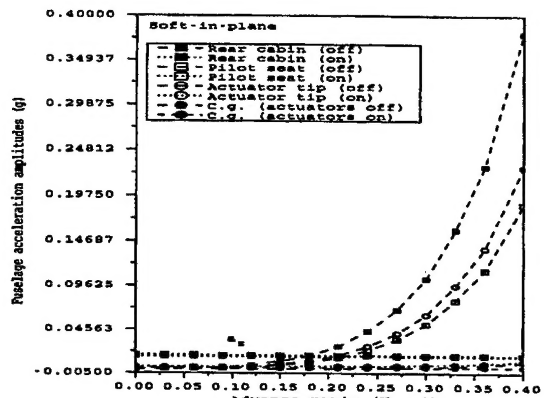

Figure 3: Vibration reduction at various fuselage locations (g)

the corners of the rigid platform. When the controller is engaged vibration levels, at various fuselage locations, are reduced to below 0.04g, as shown in Fig. 3. In Fig. 3 the curved lines indicate the uncontrolled vibration levels while the straight lines indicate the reduced vibration levels obtained after the controller is engaged. Clearly, the controller is quite effective in reducing vibration levels. As a matter of fact this active vibration control system is the only one currently used on a production helicopter, namely the EH 101 built by a Westland-Agusta consortium.

It is important to note that despite the demonstrated success of this approach in reducing vibrations, no mathematical model capable of providing a computer simulation of the operation of the ACSR system existed. Therefore all the research in this area was experimental and it relied primarily on empirical considerations. Lack of such analytical models prevented computer simulations,

which are much cheaper to conduct than flight tests, and furthermore it also prevented the fundamental understanding of the approach. Such understanding is critical when attempting to apply this approach to a number of different helicopter configurations. Therefore, the overall objective of our research activity was to develop such an analytical model, which would allow computer simulation of the ACSR approach, and provide the fundamental understanding of the approach, that is required in order to be able to use on numerous other helicopter configurations.

The primary objectives of our research activity were:

- Development of an aeroelastic response model capable of simulating the behavior of a refined coupled rotor/flexible fuselage model in forward flight, including the ACSR platform, shown in Fig.1 , together with the actuators used for vibration reduction. The output from this simulation model consists of the hub shears and hub moments, as well as three acceleration components at various fuselage locations.

- Modeling of the closed loop vibration reduction in the flexible helicopter fuselage using two different control algorithms. A basic algorithm, denoted by the term BACSR algorithm, and a more refined control algorithm utilizing the internal model principle, denoted the IMP algorithm.

- Perform trend studies of vibration reduction throughout the flight envelope of the helicopter, using both control algorithms, so as to gain fundamental understanding of the physical mechanism of vibration reduction using ACSR.. In these trend studies actuator power, control effort and the optimal location of the acceleration sensors required for effective vibration reduction were all carefully examined.

APPROACH AND MATHEMATICAL MODEL

The approach selected to achieve the objectives listed in the previous section was to develop a refined coupled rotor/flexible fuselage aeroelastic response analysis suitable for the modeling of vibration reduction based upon the ACSR approach [1]*. This aeroelastic response model has been combined with a controller using a disturbance rejection algorithm [2-5]. The coupled rotor/flexible fuselage model has a provision for incorporating an ACSR platform, which consists of a rigid rectangular plate inserted between the rotor and the flexible fuselage. At the four corners of the platform (see Fig. 1) four high frequency force actuators, shown by the dark vertical lines in Fig. 1, are modeled. These actuators produce very small displacements, accompanied by substantial oscillatory forces [2-5].

The mathematical model and the method of solution used are concisely described in the following paragraphs The coupled rotor flexible-fuselage model developed in the course of our research is capable of representing a flexible hingeless rotor combined with a flexible fuselage, a platform for the ACSR system (on which the rotor and the gearbox are mounted) and four high frequency force actuators located at the corners of this platform, as shown in Fig. 1. The model is capable of representing both four bladed (as shown in Fig. 1) as well as five bladed rotors.

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*The references quoted in square brackets are given in the publication list provided at the end of this document.

For clarity, the description of the model is separated into its primary components: the rotor, the fuselage including the ACSR platform and actuators, the method of solution, and the controllers.

The Rotor Model - is based on a flexible hingeless model with coupled flap-lag-torsional dynamics, and geometrically nonlinear terms due to moderate blade deflections. Aerodynamic loads are based on a modified Greenberg theory, with the effects of reverse flow included. Distributed aerodynamic, inertial and gravitational loads are obtained explicitly, using MACSYMA. An ordering scheme is used to neglect higher order nonlinear terms [1], this implies that terms of order ε^2 are negligible to terms of order one, i.e.

$$1+O(\varepsilon^2) \cong O(1)$$

where ε is a quantity denoting the order of magnitude of the blade slopes.

The Fuselage Model – the elastic fuselage is represented by a complete three-dimensional structural dynamic model, shown in Fig. 1. A collection of finite elements (i. e. finite element library), developed for our research, is used to generate the structural dynamic model of the fuselage. The elements used in the library are: beam, truss, non-structural mass, and plate elements. Considerable care is exercised in representing non-structural masses in the fuselage, such as: the fuel tank, engine, transmission, gearing, payload, etc. All non-structural mass elements have three translational and three rotational nodal degrees of freedom.

The ACSR Platform and Actuators – the ACSR platform consists of a rigid rectangular plate inserted between the rotor and the flexible fuselage, shown in

Fig. 1. At the four corners of the platform there are four high frequency force actuators, capable of producing considerable force, with very minute displacement (i. e. stroke). The heavy vertical lines, at the corners of the platform, in Fig. 1 depict the actuators. Provision is made for computing (or measuring) he three acceleration components, at a discrete number of fuselage locations, such as: the pilot seat, mid-cabin and rear-cabin locations.

Solution Procedure for Fuselage Vibrations – the spatial dependence in the blade equations of motion is eliminated using Galerkin's method [1] employing three flap, two lag and two torsional modes, for each blade. The finite element model of the fuselage has approximately 1000 degrees of freedom, these are reduced by using the first ten elastic fuselage modes. The coupled rotor/flexible fuselage equations are solved by using a coupled trim-aeroelastic-response solution; based on propulsive trim. The solutions are obtained from the harmonic balance method employing six harmonics, for a four-bladed rotor. Satisfying exact force and moment equilibrium equations at the rotor hub enforces proper coupling between the rotor and the flexible fuselage.

The Control Approach – a particularly suitable control approach for vibration reduction in rotorcraft is the disturbance rejection approach, since the frequency of the excitation is known and equal to the blade passage frequency (N_b/rev), where N_b is the number of blades. The overall control loop is shown in Fig. 2. The mathematical model of the ACSR system, including sensors and actuators [2-5] is combined with the aeroelastic response model representing the coupled rotor/flexible fuselage vibrations. The controller can driven by two separate control algorithms. The first is a basic control algorithm denoted by the term BACSR-algorithm, which has been employed in Refs. 2 and 3. The second is a more refined

algorithm based on the internal model principle, this is denoted as the IMP-algorithm. The internal model principle improves the performance of the controller by canceling the neutrally stable modes on the imaginary axis of the disturbance signals, and duplicating these modes inside the loop.

RESULTS

The mathematical model developed in the course of this research was used in Ref. 1 to study extensively vibrations in a coupled rotor flexible/fuselage system resembling an MBB BO-105 helicopter. Oscillatory hub shears and moments, as well as acceleration components, at various fuselage locations were simulated for this soft in plane helicopter. Simulations confirmed the validity and reliability of our model.

Subsequently in Ref. 2, the simulation capability was used to demonstrate vibration reduction using the BACSR-algorithm, for four bladed rotors. Vibration reduction below 0.05g was obtained throughout the whole flight envelope of the helicopter. It was also shown that since the vibration reduction system operates entirely in the hub fixed, non-rotating, system; vibration reduction has no influence on the airworthiness of the helicopter. However, it was found that while remarkable levels of vibration reduction were achieved, the actuator forces needed for vibration reduction could be quite high (10,000 lbs.) for certain actuators.

Extensive studies were conducted in Ref. 3 on a soft-in-plane four bladed hingeless rotor combined with the flexible refined fuselage model. The control approach was based on a simple disturbance rejection algorithm. The results demonstrated both: (1) the comprehensive capabilities of the coupled rotor/flexible fuselage model by modeling detailed vibration levels at specific locations in the

fuselage, and (2) vibration reduction capability of the active controller operating in the closed loop mode which reduces acceleration levels at specified fuselage locations below 0.05 g. Figure 3 is a typical result obtained from this simulation.

Subsequently, in Refs. 4-5 a more complicated disturbance rejection approach using IMP-algorithm [4,5] to enhance the performance of the controller was implemented, and further vibration reduction studies were carried out. The controller was successful in reducing vibrations below 0.04g throughout the whole flight envelope. Furthermore the actuator forces required with the IMP-algorithm were significantly lower (by a factor of two or more), when compared with those needed for the BASCR-algorithm.

Power requirements for implementing the vibration reduction were also simulated, and control power for vibration reduction was very low, and it varied between 1-2 horsepower. These low power requirements were entirely consistent with the behavior obtained by Westland during the flight testing of the ACSR system.

ACCOMPLISHMENTS

The primary accomplishments of this research activity are summarized below.

- A refined coupled rotor flexible/fuselage aeroelastic response model for vibration reduction studies in helicopter fuselages was developed. The fuselage contains the provision for modeling a novel type of vibration reduction system, denoted the ACSR system. Furthermore, the fuselage is represented by a detailed finite element model capable of describing accelerations levels at any fuselage location.

- Extensive trend studies with two separate control algorithms, the simpler BACSR-algorithm, and a more refined IMP-algorithm, have been conducted and extensive vibration reduction throughout the whole flight envelope of the helicopter was demonstrated. For the IMP-algorithm vibration levels were below 0.04g and control force requirements were quite practical.

- Power requirements for implementing the control were low (less than two horsepower) this computational result is consistent with the flight test results obtained by Westland Helicopters.

- The ACSR system has no influence on vehicle airworthiness, because it operates in the non-rotating reference frame. This is an advantage when compared with all other active vibration control schemes, which are implemented in the rotating frame.

- The study made a major contribution towards providing a physical understanding of the ACSR approach, the selection of the control algorithms and the optimal location of the sensors needed for vibration measurement.

- One Ph. D. student (Dr. Thiem Chiu) graduated at the end of 1996, and four conference papers and one journal paper (see list of publications) were published in the course of this research.

- Under an ASSERT grant connected to this parent grant another student (Richard Cribbs) is making major improvement to the model, by improving the aerodynamic representation. Two papers from this research activity will be published shortly.

LIST OF PUBLICATIONS PRODUCED UNDER THE GRANT (References)

1. Chiu, T. and Friedmann, P. P., " A Coupled Rotor/Flexible Fuselage Aeroelastic Response Model for ACSR", AIAA Paper No. 95-1226-CP, Proceedings of the 36th AIAA/ ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, New Orleans, LA, April 1995, pp. 574-600.

2. Chiu, T. and Friedmann, P. P., " ACSR System for Vibration Suppression in a Coupled Rotor/Flexible Fuselage Model", AIAA Paper No. 96-1547 Proceedings of the 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Salt Lake City, Utah, April 1996 pp. 1972-1990.

3. Chiu, T. and Friedmann, P. P., "Vibration Suppression in Helicopter Rotor/Flexible Fuselage System Using the ACSR Approach with Disturbance Rejection", Proceedings of the 52nd Annual Forum of the American Helicopter Society, June 4-6, 1996, Washington, D. C., pp. 736-757.

4. Chiu, T. and Friedmann, P. P., "An Analytical Model for ACSR Approach for Vibration Reduction in a Helicopter Rotor/Flexible Fuselage System", Paper No. 11, Proceedings of the 22nd European Rotorcraft Forum, Brighton, UK, September 17-19, 1996, pp. 11.1-11. 19.

5. Chiu, T. and Friedmann, P. P., "An Analytical Model for ACSR Approach for Vibration Reduction in a Helicopter Rotor/Flexible Fuselage System", The Aeronautical Journal, Vol. 101, No. 1009, Nov. 1997, pp. 399-408.